XI. *On the Affections of Light transmitted through crystallized Bodies. By* David Brewster, *LL. D. F. R. S. Edin. and F. S. A. Edin. In a Letter to Sir* Humphry Davy, *LL. D. F. R. S.*

Read December 23, 1813.

DEAR SIR,

IN a former paper* on "Some Properties of Light," which I took the liberty of addressing to you, and which the Royal Society honoured with a place in their Transactions, I attempted to give a brief abstract of a set of experiments on the Properties of transparent Bodies in refracting, dispersing, and polarising the rays of Light. An account of the instruments and methods employed in these experiments has since that time been published in my "Treatise on new philosophical Instruments."

From the general object of these researches, however, I have been allured into a new field of inquiry, by the discovery of a singular property of light transmitted through the agate, and the prosecution of the views which it suggested has led to some very extraordinary results, which, while they seem to conduct us into the very mysteries of physical optics, exhibit at the same time a series of appearances which far surpass, both in splendour and variety, all the phenomena of light under its usual transformations. In again soliciting you to communicate these observations to the Royal Society, I trust I need offer no apology. They are closely allied with that science which you have so widely extended by the most profound and brilliant

* Phil. Trans. for the year 1813, p. 101.

discoveries; and it is probably from the cultivation of this department of physics, that philosophy will be enabled to unfold the secrets of double refraction, to explain the forms and structure of crystallized bodies, and to develope the nature and properties of that ethereal matter, which, while it enlivens all nature by its presence, performs also a capital part in the operations of the material world.

The different subjects of which I mean to treat in the following letter may be included under five heads.

I. On the polarising power of the agate.

II. On the structure of the agate as connected with its optical properties.

III. On the peculiar colours exhibited by the agate.

IV. On the depolarisation of light.

V. On the elliptical coloured rings produced by obliquely depolarising crystals.

I. *On the polarising Power of the Agate.*

I have already shewn, in a former paper, that a ray of light transmitted through a plate of agate cut by planes perpendicular to the laminæ of which it is composed, suffers polarisation like one of the pencils formed by double refraction. If the light thus polarised is incident at a particular angle upon any transparent body, so that the plane of reflection is perpendicular to the laminæ of the agate, it will experience a total refraction; if it is transmitted through another plate of agate, having its laminæ at right angles to those of the plate by which the light is polarised, it will suffer total reflection; and if it is examined by a prism of Iceland crystal turned round in the hand of the observer, it will vanish and reappear in every quadrant of its circular motion.

The pencil of rays to which this remarkable property is communicated is surrounded by a large mass of nebulous light, which extends about 7° 30′ in length, and 1° 7′ in breadth on each side of the bright image.* This nebulous light never vanished with the bright image which it enclosed, but was obviously affected with its different changes, increasing in magnitude as the bright image diminished, and diminishing as the bright image regained its lustre. From this circumstance I was led to conjecture " that the structure of the agate was in " a state of approach to that particular kind of crystallisation " which affords double images, and that the nebulous light was " an imperfect image arising from that imperfection of struc- " ture."

On the supposition that this conjecture was well founded, I imagined, in conformity with the general analogy of all doubly refracting crystals, that the bright image and the nebulous light were produced by two different refractive powers, and I expected to separate the one from the other by forming the agate into a prism with a considerable refracting angle. Every attempt of this kind, however, was fruitless: no perceptible separation of the images was effected by any of the prisms which I employed, and I was therefore obliged to abandon this mode of investigation.

Having procured a plate of agate remarkably thin and transparent, I admitted a beam of light from the sky into a dark

* On each side of the bright image I have observed a condensation of the nebulous light resembling two imperfect images of the luminous body. These imperfect images, which increase in number by inclining the agate, are slightly tinged with the prismatic colours, which evidently belong to that class of phenomena which have been so ably treated by Dr. THOMAS YOUNG, in his late work on Medical Literature.

room through a narrow rectangular aperture. When this aperture was viewed through the agate, it was surrounded with a very considerable nebulosity; and by interposing a prism of Iceland spar between the agate and the eye, and giving it a motion of rotation, the nebulous light became very dense when the bright image vanished, and almost completely disappeared when the bright image had reached its greatest brilliancy. The bright and the nebulous images, therefore, comported themselves exactly like the two images formed by doubly refracting crystals; and the small portion of nebulous light, which surrounded the bright image at its maximum lustre, was obviously produced either by the imperfect polish of the agate, or by its not being cut exactly at right angles to the plane of its laminæ.

It will be seen from a subsequent section of this letter, that light polarised by the agate, or by any other means, is depolarised, or partly restored to its original state, by being transmitted in a particular direction through a plate of mica, or any other crystallized body. I therefore interposed a plate of mica between the agate and the Iceland spar when the nebulous light had nearly disappeared, and having adjusted it to the depolarising position, the nebulous light was instantly revived round the bright image, while the other bright image which had disappeared resumed its place in the middle of the other nebulous mass.

When a pencil of light polarised and afterwards depolarised, in a manner to be afterwards described, is transmitted through a plate of agate, the *red** rays go to the formation of the bright

* The *red* and the *green* are complementary to each other. The same result is obtained if the *blue* and *yellow*, or any other two complementary colours are used.

image, while the *green* rays compose the nebulous light, so that we have a *red bright image* enveloped in a *cloud* of *green light*. By turning round the agate 90° the bright image is formed by the green rays, while the nebulous image consists of the red rays, so that we have a *green bright image* encircled by a mass of *nebulous red light*. If in the place of the agate we substitute a doubly refracting crystal, it will always be found that the ordinary image is green when the extraordinary one is red, and that they assume these colours alternately during the motion of the prism round the axis of vision.

From these experiments, we may consider it as demonstrated, that the nebulous light has the same relation to the bright image, as the first has to the second image of all crystals that have the property of double refraction.* It does not appear, however, that the nebulous image is produced by a greater refractive power than that by which the bright image is formed. There is on the contrary every reason to conclude, in opposition to the analogy of all doubly refracting † crystals, that the agate gives two images and polarises them like other crystallized bodies, while the one image is placed exactly in the centre of the other.

II. *On the Structure of the Agate as connected with its optical properties.*

When we examine a piece of transparent and well polished agate, we perceive a number of bands or stripes, which are

* See Edinburgh Trans. Vol. VII. Part II.

† It will be seen from a subsequent paper, that many other bodies both of mineral, animal, and vegetable origin have the property of forming two images polarised in an opposite manner, but not produced by two different refractive powers.

the sections of a succession of laminæ that are sometimes parallel, but in general concentric. These laminæ are often of a milky white colour when seen by reflected light, and sometimes nearly as transparent and colourless as glass, and the white laminæ commonly alternate with the transparent ones. The laminæ which are white when seen by reflected light, are brown by transmitted light, and the intensity of this brown colour increases with the thickness of the plate of agate. The transparent laminæ exhibit three varieties of structure.

The *first variety*, which appears to be the coarsest, consists of a number of small serpentine lines like the figures 333333, lying parallel to each other, and closely resembling the surface of standing water when ruffled by a gentle breeze, or the sandy bottom of a slow moving stream. These serpentine lines are always arranged in a direction parallel to the laminæ, and are seen very distinctly even when the agate is so thin as the 150th part of an inch.

The *second* variety of structure differs from the first, only in the serpentine lines having a much smaller size; and the laminæ which have this structure appear the finest and most transparent.

The *third* variety has no serpentine lines, and does not appear to differ from other semi-transparent bodies. It admits the light more copiously in all directions than any of the other structures, and as it does not polarise it in a similar manner, we may consider it as possessing, in a different way, that kind of crystallisation which polarises the incident light by separating it into two pencils.

The white veins sometimes exhibit the first variety of structure, but in several specimens the veins appear to be fibrous

in their structure, the fibres stretching at right angles to the laminæ through the whole of their thickness.

These different structures will be better understood from fig. 1 and 2 of Plate V. Fig. 1, represents the specimen of agate with incurvated veins which I have noticed in a former paper.* It is composed of two veins, AB, CD, and three transparent portions AEB, ABDC, and CFD. The transparent portions exhibit the *second* variety of structure, though the small serpentine lines are not so distinctly marked as in other specimens. The two veins AB, CD, are both white when seen by reflected light. The breadth of AB is one-tenth of an inch and its radius of curvature $1\frac{1}{2}$ inch, and it consists of *four* smaller veins *mn*, *op*, *qr*, *wx*. The light reflected by *mn* is a paler white, and the light transmitted by it a lighter brown than in the other parts of the vein. The light which *op* reflects is of a brighter white, and that which it transmits of a deeper brown than in the other parts of the vein, and at the junction of *mn* and *op* there are several tufts of fibres of the same character as *op*. The other divisions of the vein *qr* and *wx* are of an intermediate character between *mn* and *op*. The vein CD resembles the division *mn*, and possesses, like AB, the fibrous structure already described. The thickness of the plate AEDC is one-fiftieth part of an inch; AC is three-tenths of an inch; and a line AC forms an angle of about 25° with a plane perpendicular to the laminæ.

Figure 2, represents another specimen of agate of a different character. It consists of transparent portions AB, BC, CD, DE, EF, separated from each other by white veins B*b*, C*c*, &c. and distinctly exhibiting the *second* variety of structure; and

* See Phil. Trans. 1813, Part I.

of other transparent portions FG, GH, HI, IK, KL, separated by similar veins G*g*, H*h*, &c. but exhibiting the *first* variety of structure. All the veins possess a structure approaching to that of the first variety, G*g*, K*k* exceeding the rest in the intensity of the light which they reflect and transmit.

If we measure the quantity of light transmitted through a plate of agate containing veins, it will be found to be a maximum when the direction of the incident rays is parallel to the interior surfaces of the veins. When the light, however, is transmitted through a part of the agate of an uniform transparency, and perfectly free from veins, the same result will be obtained, the intensity of the light being a maximum when its direction is parallel to that of the laminæ.

If AB, fig. 3, be a section of the specimen of agate represented in fig. 1, and *mn*, *op*, the direction of the laminæ inclined 25° to the surfaces of the plate, rays of light incident in the direction RS parallel to *mn* are more copiously transmitted than when they are incident in any other direction. When the pencil of light falls in the direction TV, its lustre suffers a great diminution: the light gradually assumes a red colour, and vanishes altogether when the obliquity is considerable. But if the pencil is incident at the same angle on the opposite side, as PQ, its lustre suffers very litle diminution, and its colour is not sensibly altered.

These facts admit, to a certain extent, of an easy explanation if we suppose that the plate of agate consists of laminæ *mn*, *op* imperfectly transparent, alternating with laminæ *cd*, *ef*, which are more pervious to light, a structure which is indicated by the existence of a bright and a nebulous image. In this case the intensity of the light will obviously be a maximum

when the ray RS is parallel to *mn*, and a ray PQ will, within certain limits, suffer less diminution of lustre than a ray TV falling with the same angle of incidence on the other side of RS.

When RS and *mn* are perpendicular to the surfaces of AB, and when PQ and TV form equal angles with the perpendicular RS, their intensity should be equal; but this is by no means the case, for the transmitted light which is incident on the side T of RS appears to have a different character from that which is incident on the other side. We must therefore suppose that there is some other peculiarity of structure in the agate, connected probably with that particular kind of crystallisation which polarises light, to which this curious fact must be ascribed.*

The intensity of the light transmitted by the agate is likewise affected by its polarising property. If a ray R*r*, Plate V., fig. 4, is incident upon a piece of agate AB, so as to be polarised by reflection from the second surface, then, since it is polarised during its passage from *r* to E, the bright image will suffer total reflection at E, while the nebulous image will be transmitted like common light in the direction EG. If the agate is now turned round 90° the nebulous image will suffer total reflection at E, while the bright image will penetrate the second surface at E like common light. When the incident ray R*r* has different obliquities and the agate intermediate positions, the intensity of the transmitted light will be more or less affected by its polarising power.

The preceding observations on the laminated structure of

* See Edinburgh Transactions, Vol. VII. Part II.

the agate enable us to give a satisfactory explanation of so m singular appearances exhibited by that mineral.

In the specimen shewn in Plate V., fig. 5, the black lines represent the veins, and consequently the direction of the laminæ, and the dotted lines *ab*, *ac*, *cm*, *ck*, &c. are drawn through the vertices of the angles made by the veins; and consequently by the laminæ whenever they change their direction. When light is transmitted through a piece of agate of this description, the planes A*acm*, *mck*, *ngf*, *nhg* have the appearance of being differently inclined to one another, and transmit different quantities of light. If the veins and the laminæ preserved the same inclination to the surface of the plate of agate when they changed their direction at the lines *ac*, *cm*, *de*, the phenomenon which has been mentioned could not take place; but whenever the laminæ change their direction, their inclination to the surface likewise changes, and therefore the intensity of the transmitted light experiences a corresponding variation as the rays have to traverse different lengths of the imperfectly transparent laminæ.

When the veins and the laminæ are incurvated like those in the portion A*acm*, their inclination likewise changes, but as this change is gradual and not sudden, as in the former case, the intensity of the transmitted light suffers a gradual variation, and the portion A*acm* has the appearance of being concave. When the laminæ therefore are arranged in a circular form, they will resemble a number of dimples, the apparent concavity of which will in some cases depend on the curvature of the laminæ, and will exhibit the phenomenon of the *hammered agate*.

III. *On the peculiar Colours exhibited by the Agate.*

In my former letter on the polarising power of the agate, I noticed the existence of a coloured image which appeared on each side of the common colourless image, and which was polarised in a similar manner. I have since observed the same phenomenon in other specimens, and though I have not been able to discover its cause, I trust the following observations will be of some service to future inquirers.

In the specimen represented, in Plate V., fig. 2, the colours appear only when the rays of light are transmitted through the veins B, C, D, E, F, G, H, I, K, or through the coarse grained portions F*g*, G*h*, H*i*, I*k*, K*k*L, and when these parts are covered, no colour is perceived. If the eye, therefore, is placed behind any of the coarse grained parts, and close to the agate, a colourless image of a candle will be visible, and on each side of it a highly coloured image forming an angle of $10°\frac{1}{2}$ with the colourless image. The colours, which are extremely brilliant, are blue, green, yellow, and red, reckoning from the common image. A second image coloured in a similar manner, but considerably fainter, is distinctly seen forming with the colourless image an angle of about 21°. When the agate is held some inches distant from the eye, the colours appear diffused over the surface of the coarse grained portions, and when the light is strong, the phenomenon is uncommonly brilliant. When the vein B*b* is a pale blue, at a certain distance from the eye, C*c* and D*d* are of the same colour, E*e* is greenish, F*f* is yellowish, FG*gf* is pale red, and the red colour is more intense towards L*k*. By a gentle mo-

tion of the agate the colours of these portions instantly change, a particular colour being always produced in the same portions at a particular angle of incidence. The veins G*g*, H*h*, I*i*, and K*k* are, however, green when the surrounding portions are red, and red when the surrounding portions are green, from which it follows that these veins produce a particular colour at a different angle of incidence from the adjacent portions. In another specimen of agate, very like the preceding, the same phenomena are distinctly visible, and the coloured image forms the same angle with the common image. In a third specimen, belonging to ROBERT FERGUSON, Esq. of Raith, the colours are exhibited in the most splendid manner. A semitransparent and irregularly elliptical zone, about six and a half inches in circumference and three tenths of an inch broad, has the *first* variety of structure, and forms the coloured image at a distance of $13\frac{1}{2}°$ from the common image.

In the specimen represented in Plate V., fig. 1, the colours are visible only in the vein AB; but here the angle of the first coloured image with the common image is 28°, while that of the second image, which is very faint, is only a little greater. The other vein CD, which to all appearance has the same structure as AB, and which differs from it only in being a little thinner, exhibits no colours; but there is a small stripe *st* at its edge where the colours are very distinct. This circumstance induced me to think that the colours depended on the thickness of the plate, as well as upon its structure; but upon grinding a hollow place *mvw* in the vein AB, so as to make the agate remarkably thin, I found that it gave the same colours as before. A similar experiment was made with another piece of agate, and the result

was the same, though the thickness of the plate could not exceed the 400th part of an inch. The colours indeed were rendered more brilliant by the increased transparency of the agate, but in other respects they experienced no change. In another specimen, of which it is unnecessary to give a particular description, the coloured image formed an angle of about 34° with the colourless pencil, and the different veins produced the same colour at different angles of incidence.

In attempting to explain these appearances, I at first imagined that the colours arose from the polarisation of the transmitted rays, and that they were analogous to the colours of plates of mica and topaz which I have described in another place. I found, however, from several experiments, that the coloured image is equally distinct in every position of the agate; that it is alike produced by polarised or depolarised light, and that it suffers no change either when examined by a plate of agate or by a doubly refracting crystal.

The phenomenon which we have described must therefore be considered as a new case of the production of colour, and though we do not pretend to point out its cause, yet it obviously depends upon a particular structure which is possessed only by some portions of the agate, and admits of such variations as to produce the same colours at different angles of incidence.

IV. *On the depolarisation of Light.*

In the fourth book of my Treatise on new Philosophical Instruments, I have already shewn that almost all transparent

crystals possess in two positions the singular faculty of depolarising light, or of depriving it of the property which it acquires by transmission through the agate, while in other two positions of the depolarising crystal, the polarity of the light suffers no change. Thus in Plate V., fig. 5, let ABDC, be a piece of mica or of any other crystallized body interposed between a plate of agate and a prism of Iceland spar when one of the images has vanished, and let GH be parallel or perpendicular to the laminæ of the agate when the vanished image continues invisible. This line I have called the *neutral axis*, as no effect is here produced upon the polarised light. By turning the mica round, the vanished image will gradually appear, and when the line AD comes into a vertical position, it will be restored to its full lustre, and will never again vanish whatever be the position of the Iceland spar. The line AD I have therefore called the *depolarising axis*, as the light in passing through it has been deprived of the polarity communicated by the agate, and which prevented it from penetrating the rhomboid of Iceland spar.

By continuing the motion of the mica, it will be found that EF is also a neutral axis, and BC a depolarising axis. The depolarising axes are common to almost all crystallized substances, and what is very singular, I have discovered them in horn, gum Arabic, glue, tortoise-shell, caoutchouc, gold beater's skin, amber, mother of pearl, camphor, spermaceti melted and cooled, bees' wax melted and cooled, adipocire melted and cooled, manna, oil of mace, acetate of lead melted and cooled, human hair, bristles of a sow, human cornea, cornea of a fish, cornea of a cow, and imperfectly in some pieces of plate glass.

Plates of mica, however, while they possess the properties of all depolarising crystals, exhibit phenomena peculiar to themselves. If the neutral axis GH of a plate of mica is inclined forwards so as to make a considerable angle with the horizon, the image that was formerly invisible will start into existence, and therefore the neutral axis GH is accompanied with an oblique depolarising axis N*n*. This oblique axis is also possessed by topaz, rock crystal, and many other crystallized bodies. In making the same experiment with the depolarising axis of the mica, I observed the image to vanish in the direction M*m* and P*p*, which I considered as oblique neutral axes, but I have since found that this was owing to the polarisation of the pencil by oblique transmission, a property of light which I had not then discovered.

We have hitherto considered the depolarisation of light as effected by two separate bodies, one of which polarises the incident rays, while the other deprives them of the polarity which they have thus acquired; but in all bodies that possess oblique depolarising axes, light may be polarised and depolarised by the same crystal. Thus if AB*ab*, Plate V., fig. 7, be a plate of topaz having DE for its oblique depolarising axis, and if a ray RR′ of common light is incident at R′ with such an obliquity that it is polarised by being reflected at C from the posterior surface *ab*, then the ray *rr′* will be depolarised in its passage from C to *r* along the oblique axis of depolarisation, and the emergent ray *rr′* will be depolarised light. Hence it follows that the angle DC*b*, which the oblique depolarising axis makes with the posterior surface *ab*, is nearly equal to the

complement of the angle OC*r*, at which light is polarised by reflection at C.*

V. *On the elliptical coloured rings produced by depolarising Crystals.*

In a former work, to which I have already had occasion to refer, I have given some account of the colours which accompany the depolarisation of light, and I have particularly noticed the remarkable fact, that when a beam of white depolarised light is transmitted through a doubly refracting crystal, the red rays go to the formation of one image, while the bluish green rays go to the formation of the other image. In repeating and extending these experiments, I have been led into a new field of inquiry which has already afforded a series of instructive results deduced from a class of phenomena unquestionably the most brilliant within the whole range of optics.

The plate of topaz which was used in these experiments, is

* Since the preceding section was written, I have performed a very extensive series of experiments on the depolarisation of light, and have thus been led to a satisfactory generalisation of the phenomena. In this theory the phenomena are referred to the general principle of polarisation: such bodies as have neutral and depolarising axes are supposed to form two images polarised in an opposite manner, and either produced by the same or by different refractive powers; while those which depolarise light in every direction, like gum Arabic, caoutchouc, &c. are composed of films or layers, each of which is a doubly polarising crystal, the neutral and the depolarising axes of one film not being coincident with the neutral and depolarising axes of the rest. In a separate memoir, which I have drawn up for the consideration of the Royal Society, I have given a full account of this theory, of the experiments on which it is founded, and of the new views to which it leads respecting the formation and structure of organised matter.

about $\frac{103}{1000}$ of an inch thick, and has two natural faces which are parallel and highly polished. Its refractive power is 1.636; its dispersive power 0.024, and the angle at which it polarises light by reflection 58° 8′. It is represented in section by AB*ab*, in Plate V., fig. 8, DE being one of its depolarising axes. If a beam of *common light* RR′ is now incident on the anterior surface AB at an angle of about 60° 38′, a part of the beam will penetrate the topaz at R, and after reaching the posterior surface *ab*, it will be partly transmitted at C in the direction CF, and partly reflected in the direction C*r*, so as to depart from the point C almost wholly polarised by reflection; but in its passage from C to *r* along the oblique depolarising axis of the crystal, it is depolarised and emerges at *r*, in the direction *rr′* deprived of the polarity which it had acquired by reflection at C. If the observer now looks into the topaz in the direction *r′r*, through a plate of agate having its laminæ perpendicular to the plane of the section AB*ba*, he will perceive about ten brilliantly coloured elliptical rings, four of which, with the two central spots, are shewn in Plate VI., fig. 1.*

The following measures will convey a correct idea of their form and magnitude.

Breadth of the central spots including half the black space between them - - - -	1° 51′
Distance of the outsides of the central spots -	3 42
Transverse length of each central spot - -	5 7
Extreme conjugate diameter of *first* red ring -	7 24

* I have counted fourteen of these rings when the light was polarised by oblique transmission through a plate of mica 0.127th of an inch thick. The colours are in this case much more distinct.

Extreme conjugate diameter of second red ring	-	11°	6′
Ditto third	- -	14	48
Ditto fourth	- -	18	30
Ditto fifth	- -	22	12
Ditto sixth	- -	25	54
Ditto seventh	- -	29	36
Ditto eighth	-	33	18
Ditto ninth	- -	37	0
Ditto tenth	-	40	42
Black space between the oval centres	- -		$14\frac{1}{3}$

In order to convey a correct notion of the different colours which compose the elliptical rings, and which vary in different parts of the same ring, I have given in Plate VII., fig. 1, an outline of the first *six* rings with references to the following table, which contains the colours in five different parts of the semicircumference of each ring.

Oval central spots.
1. *Light blue* with a purplish tinge fading into *white* above, and gradually deepening into *black* below.
2. *White* fading into yellow above, and *light blue* below.
3. *Yellow* shading off into *white* below, and red above.
4. Red, with a pink tinge, and shading into *yellow* below.

I. Order.
5. *Black* fading into light blue towards 6.
6. *Light blue* fading into *green*.
7. *Yellow* shading into *red*.
8. Deep crimson.

II. Order.
9. *Blue*, very little.
10. *Green*, very little, the green beginning a little below.
11. *Yellow* shading into red.
12. Crimson.

III. Order.
13. Light blue, very little.
14. Green, very broad.
15. Crimson fainter than 12.

IV. Order.
16. Green, very broad.
17. Faint blue.
18. Faint crimson.

V. Order.
19. Very faint blue.
20. Very faint crimson.

VI. Order.
21. Still fainter blue.
22. Still fainter crimson.

I. Order.
23. Black shading off into light blue.
24. Dark green.
25. Yellow.
26. Deep crimson.

II. Order.
27. Blue.
28. Green.
29. Crimson.

III. Ord.
30. Bluish green.
31. Crimson.

IV. Ord.
32. Very faint blue. Green begins here.
33. Very faint pink.

V. Order.
34. Still fainter blue.
35. Still fainter crimson.

I. Order.
36. Black mixed with a little green.
37. Ditto.
38. Ditto.
39. Dark green, a little yellow on its upper side.
40. Red, pinkish, not very bright.

II. Order.
41. Darkish green.
42. Faint crimson.

III. Order.
43. Green.
44. Blue, very little.
45. Faint crimson.

IV. Order.
46. Faint blue.
47. Faint crimson.

All the other fringes, without this, consist of blue and pink, which grow fainter as they recede from the centre.

I. Order.
a Black.
b Dark blue approaching to black.
c Light blue shading to black.
d Whitish.
e Reddish brown of an orange cast.

II. Order.
f Very dark blue.
g Light blue.
h Yellowish.
i Pink.

III. Ord.
k Light blue.
l Yellowish green.
m Faint pink.

IV. Ord.
n Green, blue begins here and runs downward.
o Pink.

V. Order.
p Faint blue, green begins here and runs downward.
q Pink.

I. Order.
r Black.
s Faint blue shading into whitish.
t Whitish shading into faint brown.
u Faint reddish brown.

II. Order.
v Black.
w Dark blue shading into light blue.
x Brownish yellow.
y Dark pink, with a brown tinge.

III. Order.
z Pale blue shading into greenish yellow.
& Greenish yellow.
a' Pink.

IV. Order.
b' Blue, not much.
c' Green.
d' Pink.

V. Order.
e' Green.
f' Light blue.
g' Faint pink.

VI. Order.
h' Faint blue.
i' Faint pink.

If the plate of agate is now turned round 90°, so that its laminæ are parallel to the plane of the section AB*ab*, a *second set* of elliptical rings will be seen as represented in Plate VI., fig. 2, which is on the same scale as fig. 1, and which contains only the four first orders of colours, and the central spots. This new set of rings is composed of colours which are *complementary* to those in the first set. By measuring the diameters of the *red* rings in the *second set*, it will be found that they correspond with those of the *green* rings in the *first set;* the *blue* rings correspond with the *yellow;* the *green* with the *red;* and the *yellow* with the *blue;* and in the outer rings the *blue* with the *pink*, and the *pink* with the *blue*. The central spots in the *second set* exhibit the same opposition of colours to those in the *first set;* but they are smaller, and placed at a greater distance; and the space around them which was formerly *black* is now *white*.

If instead of a plate of agate we employ a doubly refracting crystal, the *first set* of rings will, in one position of the crystal, be seen in the first image; and upon turning the crystal about its axis, the *first set* will occupy the second image, and the *second set* the first image, an alternation taking place in every quadrant of the motion of the crystal. This method of viewing the rings is in some respects superior to that in which the agate is used, as the nebulous image formed by this mineral injures, in some degree, the distinctness of the image; but on the other hand, the doubly refracting crystal requires to be cut into a prism with a large angle, in order to separate the two images which it forms, and therefore it alters the shape of the rings, and produces a complete change upon their colours.*

* Since this paper was written, I have discovered a new property of light in virtue

If the emergent rays rr', instead of being transmitted through agate or Iceland spar, are reflected at the polarising angle from any transparent body having its reflecting surface parallel to the plane of the section ABab, they will exhibit the *first set* of rings; but if the reflecting surface is perpendicular to the plane of the section, the *second set* of rings will be visible. When the *first set*, thus seen by reflection, is examined through a prism of Iceland spar, it suffers no change either in the first or second image.

In these experiments the *first set* of rings is extremely distinct, as the polarising crystal extinguishes the light RS reflected from the first surface of the topaz; but the *second set* of rings is very faint, as the light RS is not extinguished by the polarising body.

When we examine the transmitted light CF, either with the naked eye or with polarising crystals, no coloured fringes are visible.

Such are the modifications which *common light* undergoes in its passage through topaz. The affections of *polarised light*, which now come under consideration, are still more varied and interesting. In my first experiments on this subject, I polarised the light by transmitting it through the agate; but I afterwards found it most convenient to communicate this property by reflection from the surface of a transparent body.

Let RR′, Plate V., fig. 9, be a beam of polarised light obtained by reflection from any transparent body GH, the plane

of which it is polarised by oblique transmission through transparent bodies. Hence, in all my experiments on the coloured rings, I find it of incalculable advantage to polarise the light by bundles of glass plates, and to use them in every case where I formerly employed agate or calcareous spar.

of reflection from GH being perpendicular to the plane of reflection from the topaz AB. A part of this beam will be reflected at C in the direction C*r*, and part of it transmitted at C in the direction CF, no light being reflected from the first surface AB. The rays transmitted at C having been polarised before their incidence at R′ are depolarised in passing from R′ to C along the oblique depolarising axis, and the rays reflected at C are polarised by reflection from the surface *ab*, and again depolarised in their passage from C to *r* along the other oblique depolarising axis.

If the observer now looks into the topaz in the direction *rr′*, he will perceive the *first* set of elliptical coloured rings, as represented in Plate VI., fig. 1. These rings are now peculiarly distinct and brilliant, and it was therefore from them that I drew up the table of colours referred to from Plate VII., fig. 1.

Let the ray *rr′* be now received upon a plate of agate having its laminæ perpendicular to the section AB*ab*, and a *third set* of rings will be seen like those in Plate VI., fig. 3. This *third set* differs from the *first set* only in the central parts. All the rings have the same colours in both, but the central spots are much smaller in the third set than in the first, and the mass of darkness with which they are surrounded encroaches considerably upon the blue part of the first ring.

In the third set of rings the distance of the outsides of the two central spots is - -	3°	3′
Conjugate diameter of each spot - -	1	1
Ditto of the black space between the spots - - - -	1	0

The *third set*, indeed, may be considered as the exact counterpart of the *second* set, all the colours of the former being

complementary to those of the latter, and the central spots having the same form and magnitude.

If the plate of agate is now turned round, so that its laminæ are parallel to the section AB*ab*, a *fourth set* of rings will be seen. This new set, which is represented in Plate VI., fig 4, is by no means brilliant, but it is distinguished from all the rest by striking peculiarities. In its general structure it resembles the *first set*, but in the middle of each central spot there is a darker spot composed of blue and red, with a little green above the blue, and every ring is divided into two rings, each of which has the same colours as the original ring. This division of the rings occupies only a part of the semicircumference of each, and is not seen beyond the third ring.

When the agate begins to move from the position which gives the *third set* of rings, into that which gives the *fourth set*, two blue spots and the divisions of the rings begin to appear at a, a, a, a, a', a', a', a', Plate VII., fig. 2, and move along the lines abc, $a'b'c'$ till they arrive at c, c, c, c, c', c', c', c', when the rings assume the appearance of the *fourth set*. If the agate performs another revolution of 90° from the position which gives the *fourth set* into that which gives the *third set*, the blue spots, and the divisions of the rings move off in the direction c, d, e, c', d', e' till the rings assume the appearance of the *third set*.

The phenomena which have now been described may also be perceived, when the polarisation of the rays rr' is effected either by a doubly refracting crystal or by reflection. In one position of the doubly refracting crystal the third set of rings is seen in the first image, and the fourth set in the second image, and they alternate in every quadrant of the motion of the crystal. When the ray rr' is reflected from a transparent

body, so that the plane of reflection is parallel to the plane of reflection from the topaz, the *fourth set* of rings will be visible.

Hitherto we have attended only to the light reflected from *ab*, the posterior surface of the topaz; but the light transmitted at C exhibits also interesting phenomena. When the observer looks through the topaz in the direction FC, so as to see the polarising surface GH, the *second set* of rings is faintly visible. They become extremely distinct, however, when viewed through a plate of agate having its laminæ at right angles to the plane AB*ab*. If the laminæ are parallel to the plane AB*ab*, the *second set* is converted into the *first set* with colours a little paler than when it was produced in the former experiments.

In the preceding experiments the plane of reflection from GH has been perpendicular to the plane of reflection from the topaz. We shall now describe the phenomena which take place when these planes are parallel to each other, an arrangement which is represented in Plate V., fig. 10.

When the observer looks into the topaz in the direction *rr'*, he will perceive the *second set* of fringes. If the rays *rr'* are transmitted through a plate of agate having its laminæ perpendicular to the plane of reflection, the *fourth set* of fringes will be seen, but they are very much fainter than they appeared in the former experiments. When the laminæ of the agate are parallel to the plane of reflection, the *second set* is faintly visible. The central spots are, however, rather larger than before, so that this set has the appearance of being the reverse of the *first* rather than of the *third* set.

When the light transmitted in the direction CF is seen by the naked eye, it exhibits the *first set* of rings. If it is examined through a plate of agate having its veins perpendicular to the

plane of reflection, the *first set* is still visible; but when the agate is turned round 90° the *second set* is perceived.

All the preceding observations were made with a plate of topaz $\frac{103}{1000}$ of an inch thick. When the plate has a greater thickness the rings are much smaller, and when it has a less thickness the rings are extremely large, so that in very thin plates, only a small portion of a ring can be perceived at once. We have already seen that with a plate $\frac{103}{1000}$ of an inch thick, the fourth red ring subtends an angle of 18° 30′. With another plate $\frac{227}{1000}$ of an inch thick, the angle subtended by the same ring is 8° 24′. But since

$$\tfrac{227}{1000} : \tfrac{103}{1000} = 18^\circ\ 30' : 8^\circ\ 24;$$

it follows *that the conjugate diameters of the rings are inversely as the thickness of the plates.*

According to the Abbé Haüy, the angle formed by two of the primitive faces of the topaz is 124° 22′; and therefore the axes or longest diagonals of the primitive rectangular prism will form angles of 60° 31′ 15″ * with a line perpendicular to the laminæ, a result which agrees so nearly with 60° 38′, the inclination of the axes of the coloured rings, that we can have no hesitation in concluding that *the axes of the coloured rings are coincident with the longest diagonals of the primitive rectangular prism.*

The rings which have now been described as produced by *topaz*, I have discovered in *rock crystal*, *mica*, the *agate*, the *oriental ruby*, the *emerald*, *native hydrate of magnesia*, *amber*, *ice*, *sulphate of potash*, *tartrate of potash and soda*, *nitrate of potash*, *acetate of lead*, *acetate of lead melted and cooled*, *prussiate of pot-*

* According to my own measurements the angle is 123° 58′, which gives 60° 28′ 26″ for the inclination of the diagonals.

ash, mother of pearl, bones of a cod, quill, the human nail, horn, tortoise shell, cornea of a fish, cornea of a cow, cornea of a man, spermaceti, RUPERT'S *drops, gum Arabic,* and *caoutchouc.*

1. *Rock crystal.* The only specimen of this mineral which I could obtain when I made the preceding experiments, was in the form of a double convex lens about $\frac{63}{1000}$ of an inch thick. It exhibited only segments of the coloured rings, but they were very large and brilliant, and afforded me the means of making a very interesting experiment with a plate of agate.

If a beam of common light is incident upon the neutral axis of this crystal, at such an angle that after reflection from its posterior surface, it shall emerge in the direction of its oblique depolarising axis, the light thus polarised by reflection and depolarised by transmission through the depolarising axis will reach the eye in the state of white light. If this light is viewed through agate, one of the coloured segments, suppose *green*, will be distinctly visible; but if the agate is turned 90° round, the green colour will be converted into *red*, and in general the colour seen in one position of the agate will be complementary to that which is seen in the other position. When the light, however, is brilliant, another very singular phenomenon presents itself. If the bright image seen through the agate is *green*, the nebulous image, in which it is inclosed, will be *red;* and when the bright image is red, the nebulous image will be green, and in general the colour of the nebulous image will be always complementary to that of the bright image. If we employ a prism of Iceland spar to examine the depolarised light, the colour of the ordinary image is always complementary to that of the extraordinary image. We may therefore consider the preceding result as an *experimentum crucis,* which

establishes the opinion respecting the structure of the agate, that has been given in another part of this paper.

2. *Mica.* The coloured rings are distinctly visible in mica, both when the light is transmitted perpendicularly through the plate, and when it is incident in the direction of its oblique depolarising axis. The irregular structure of this mineral, however, and the impossibility of procuring laminæ with parallel and even surfaces prevented me from investigating the phenomena of its coloured rings.

3. *Agate.* The only plate of agate in which I have observed the coloured rings, is cut in such a direction that it does not polarise the bright image. It possesses, however, the faculty of depolarisation, and therefore must form two bright images one of which lies immediately above the other. This plate is about $\frac{28}{1000}$ of an inch thick, contains no veins, and exhibits broad segments of coloured rings.

4. *Oriental ruby.* This doubly refracting crystal affords beautiful rings, in which, owing to the colour of the mineral, the predominant colours are crimson, light blue, and bluish green. The central spots were distinctly visible, and though the crystal was $\frac{12}{100}$ of an inch thick, the rings appeared to be larger than those given by topaz $\frac{103}{1000}$ of an inch thick.

5. *Emerald.* The coloured rings formed by this stone are principally blue and greenish yellow, the least refrangible rays being extinguished by the green colour of the mineral.

6. *Native hydrate of magnesia.* This mineral affords very distinct segments of coloured rings when the light is transmitted in a direction nearly perpendicular to the surface of the laminæ. Owing to the imperfect structure of the plates, I could not obtain a measure of the diameter of the rings.

7. *Amber.* As this substance possesses no crystalline form, and does not split into laminæ, I found it impossible to make any satisfactory experiments with it. The enormous breadth of its coloured rings was conspicuous in every specimen, but though I ground and polished more than twenty plates of it, I could not obtain one which exhibited any thing more than broad coloured segments. With a parallelopiped of amber 0.566 of an inch long, 0.300 broad, and 0.367 deep, the coloured segments were visible in every direction in which the light was transmitted. They appeared most distinct through the thickness 0.367; and through the thickness 0.566 they were still so broad, that no more than one colour of each ring could be seen. In a piece of amber $\frac{6}{10}$ of an inch thick, the rings were broader than in a plate of topaz $\frac{1}{30}$ of an inch thick.

8. *Ice.* The difficulty of making experiments upon ice without melting it, the want of a crystalline form, and the impracticability of shaping it into parallel plates prevented me from obtaining any accurate results. The following experiments, however, will throw some light upon this subject.

A piece of ice $\frac{1}{10}$ of an inch thick gave rings much broader than those exhibited by a plate of topaz $\frac{1}{30}$ of an inch thick. The rings were also seen by the reflection of common light from the posterior surface of the ice, the light reflected from the anterior surface being extinguished by a prism of calcareous spar.

A piece of ice $\frac{10}{30}$ of an inch thick exhibited rings larger than those given by a plate of topaz $\frac{2}{30}$ of an inch thick. The breadth of one of the fringes shewn by a plate of ice $\frac{94}{300}$ of an inch thick was nearly $5° 26'$, which compared with the

results already mentioned, gives $\frac{10.5}{300}$ for the thickness of a plate of topaz that would produce a fringe of the same magnitude. Hence the thicknesses of ice and topaz that give rings of equal size are as $\frac{94}{300}$ to $\frac{10.5}{300}$, or as 8.95 to 1, which is nearly the inverse ratio of $(m-1)^3$ in ice to $(m'-1)^3$ in topaz, m and m' being the indices of refraction. If we take $m = 1.307$ and $m' = 1.636$, this ratio will be nearly as 8.9 to 1. In these experiments the two oval central spots were distinctly seen.

Light transmitted at an angle of 46° through a plate of ice 1.25 inches thick gives rings of the same size as when it is transmitted at an angle of 60° 38′ through a plate of topaz $\frac{103}{1000}$ of an inch thick. By calculating the real thicknesses in the direction of the transmitted light, it will be found that the thicknesses at which ice and topaz produce rings of the same magnitude are as 8.4 to 1, a ratio not very remote from that of $(m-1)^3$ in ice to $(m'-1)^3$ in topaz.

Light transmitted at an incidence of 36° through a plate of ice $\frac{68}{100}$ of an inch thick gave rings twice as large as those shewn by a plate of topaz $\frac{103}{1000}$ of an inch thick. These thicknesses will be found, after reduction, to be as 8.2 to 1, a ratio more remote than any of the former from that of $(m-1)^3$ to $(m'-1)^3$.

A plate of ice taken from the surface of a pool of water did not appear to depolarise light, when it was incident perpendicularly: but when the angle of incidence was considerable, the light was depolarised in every direction, and the coloured rings appeared even at great obliquities.

9. *Sulphate of potash.* A plate of sulphate of potash $\frac{135}{1000}$ of an inch thick gave fringes of colour, each of which was 4° in breadth, while another plate $\frac{168}{1000}$ of an inch thick gave

fringes $3^\circ\ 12'$ in breadth. Now

$$135 : 168 = 3^\circ\ 12' : 4^\circ \text{ nearly},$$

so that the diameters of the rings are inversely as the thicknesses of the plates, as in the case of topaz. The light was incident on the sulphate of potash at an angle of 41°, which gives $\frac{179}{1000}$ for the oblique thickness of the plate $\frac{135}{1000}$ of an inch thick. Now

$$\tfrac{179}{1000} : 1^\circ\ 51' = \tfrac{209}{1000} : 2^\circ\ 2',$$

the size of the ring that would have been produced by a plate of topaz $\frac{179}{1000}$ of an inch thick, so that the thicknesses of sulphate of potash and topaz that produce equal rings are as 1.85 to 1, which is not very far from the ratio of $(m-1)^3$ to $(m'-1)^3$. If we take $m = 1.509$ and $m' = 1.636$ this ratio will be as 1.95 to 1.

10. *Tartrate of potash and soda.* The neutral axes of this salt are parallel and perpendicular to the axis of the prism, and it possesses an oblique depolarising axis along which the coloured rings are visible. The thicknesses of this substance and of topaz, at which equal rings are produced, are as 31 : 16, which is almost exactly the ratio of $(m-1)^3$ to $(m'-1)^3$. The value of m' in the tartrate being 1.515.

11. *Nitrate of potash.* This salt, which is remarkable for its optical properties,* exhibits along the axis of the hexaedral prism a series of beautiful miniature rings, *twelve* of which are distinctly visible. In a plate of the nitrate of potash $\frac{17}{100}$ of an inch thick, the fourth ring subtended an angle of $5^\circ\ 45'$, whereas, in a plate of topaz $\frac{461}{1000}$ of an inch thick, it subtended an angle of $8^\circ\ 25'$. But

* I have endeavoured to give a full account of these in the Transactions of the Royal Society of Edinburgh, Vol. VII. Part II.

$$5^\circ\ 45' : 8^\circ\ 25' = \tfrac{461}{1000} : \tfrac{675}{1000}$$

the thickness of topaz that would give the fourth ring a diameter of $5^\circ\ 45'$. Hence the thicknesses at which the nitrate of potash and topaz produce rings of equal magnitude are as $\frac{170}{1000}$ to $\frac{675}{1000}$, or as 1 to 3.97 nearly. But assuming the rings to vary as $(m-1)^3$, those formed by the nitrate should have been larger than those exhibited by the topaz in the ratio of $636^3 : 515^3$, or nearly 1.88 to 1. Hence the rings formed by nitrate of potash are 1.88×3.97, or 7.5 times smaller than they should be if their conjugate diameters had varied as $(m-1)^3$.*

12. *Acetate of lead.* This doubly refracting crystal melts at a temperature not much greater than that which bees' wax requires, and it takes a long time to cool and crystallize. When it is formed by heat into a thin film between two plates, the crystals shoot from different centres, and exhibit by polarised light the most beautiful alternations of the prismatic colours. When the eye is kept at a distance from the plate, the colours radiate like the spicula of the salt, and vary at every inclination of the plate.

13. *Mother of pearl.* The coloured rings are extremely brilliant in this substance when the polarised light is transmitted almost perpendicularly; but they do not appear when it penetrates by an oblique path.

The other substances, which have already been mentioned as affording coloured rings by polarised light, exhibit only imperfect segments of the fringes, but in all of them these

* The thickness of the plates of ice, sulphate of potash, and nitrate of potash, and the inclination of the incident pencil were measured in the rudest manner, as my object was merely to ascertain in general if there was any connection between the magnitude of the coloured rings and the refractive power of the body which produced them.

segments are distinctly visible, excepting in caoutchouc, where the colours are extremely faint.

It is highly probable that the coloured rings will be found in a still greater number of crystallized bodies. I have sought for them in vain in the diamond, native orpiment, Iceland spar, fluor spar, muriate of soda, carbonate of lead, carbonate of barytes, the sclerotic coat of the eye, the crystalline lens, and a great variety of other bodies, and in some of these with so much care, that they could scarcely have escaped my notice, if they did exist. It therefore still remains to be determined, what kind of crystallization is necessary to their production, and what relation exists between the magnitude of the rings and the refractive power of the body which produces them. In some of the experiments already described, the diameters of the rings seem to vary as $(m - 1)^3$, but the anomalies exhibited by amber and nitrate of potash completely prove that this is not the law by which their magnitude is regulated.

I have the honour to be,

Dear Sir,

your most obedient humble servant,

DAVID BREWSTER.

To Sir HUMPHRY DAVY, LL.D., &c. &c.

First Set. Fig. 1.

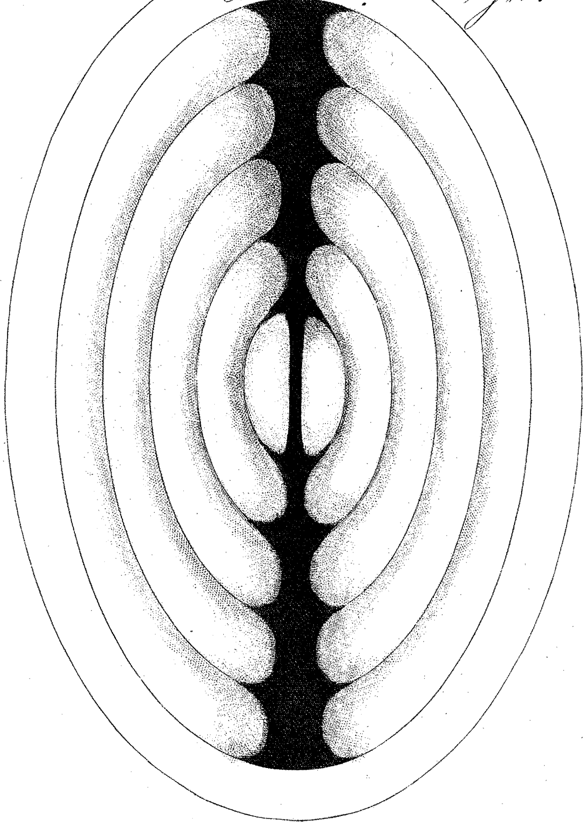
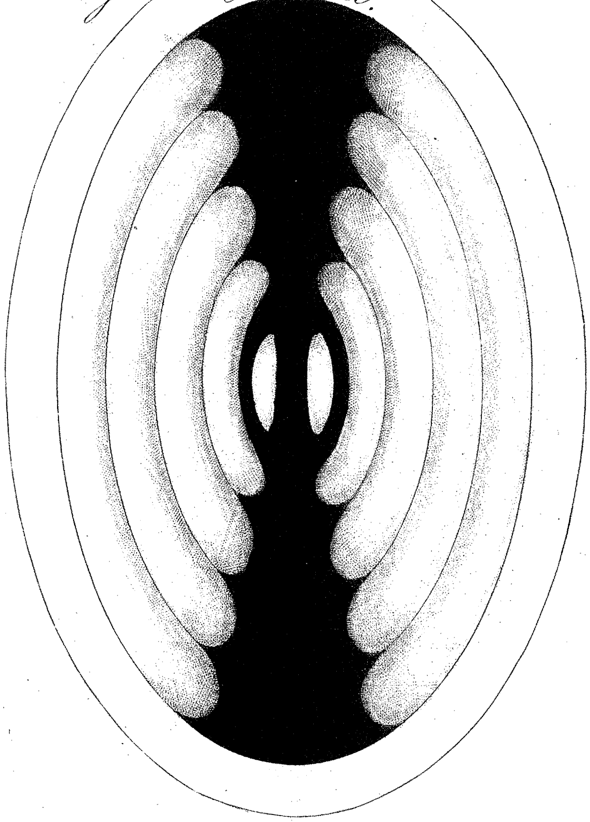


Fig. 3. Third Set.



Second Set. Fig. 2.

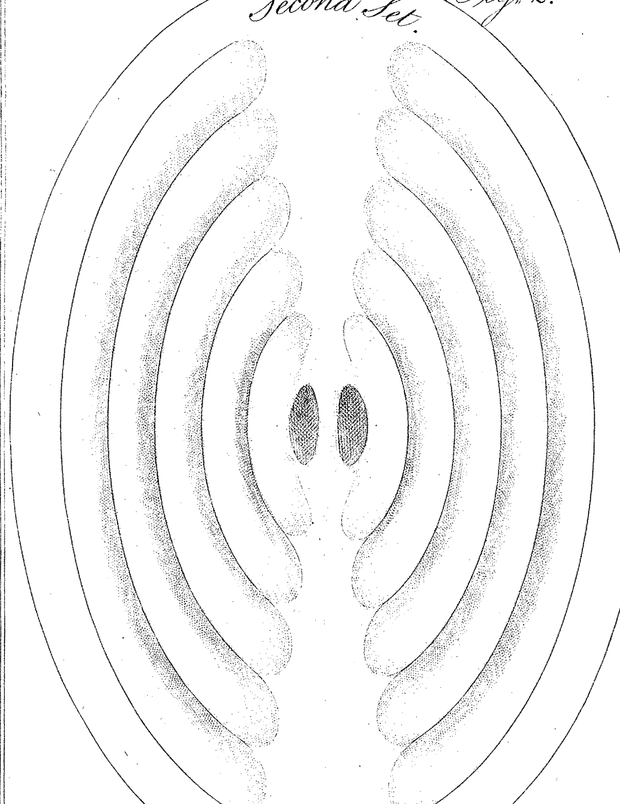


Fig. 4. Fourth Set.

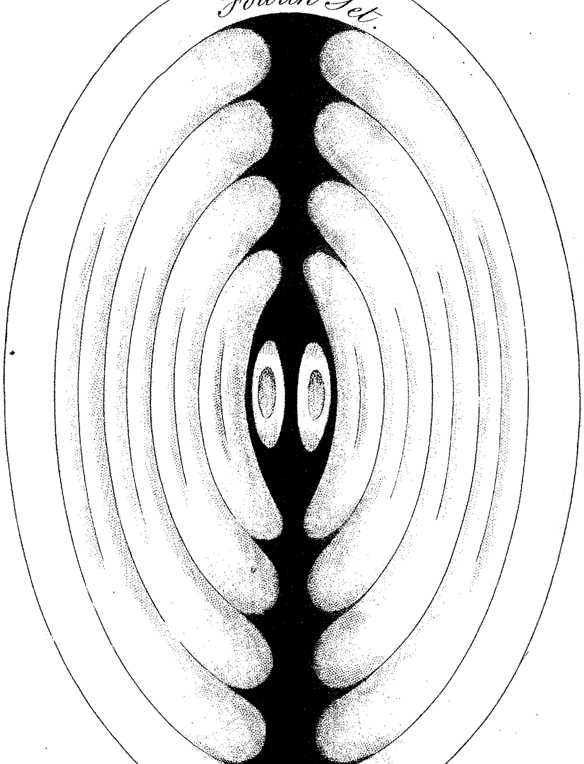


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Fig. 1.

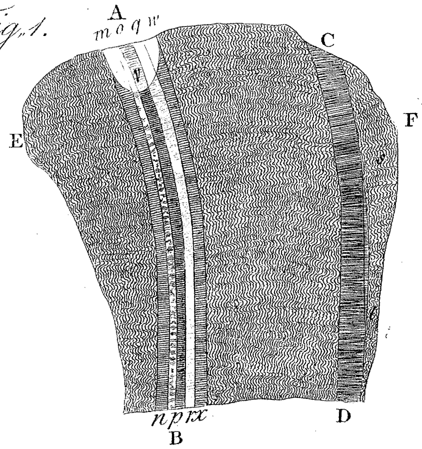


Fig. 2.

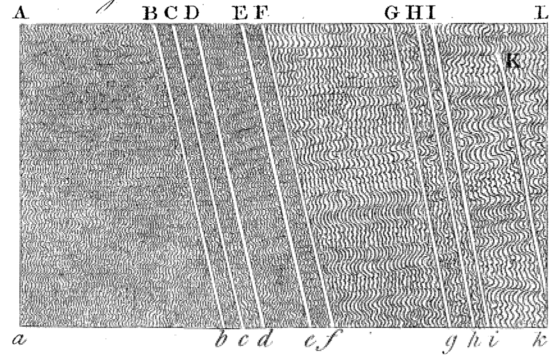


Fig. 3.

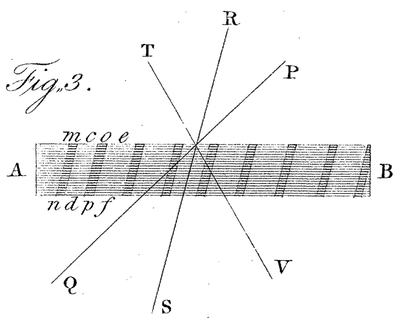


Fig. 4.

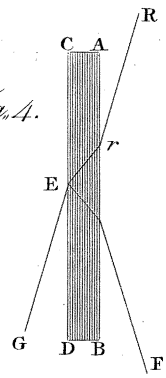


Fig. 5.

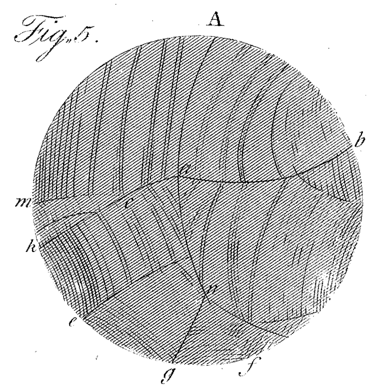


Fig. 6.

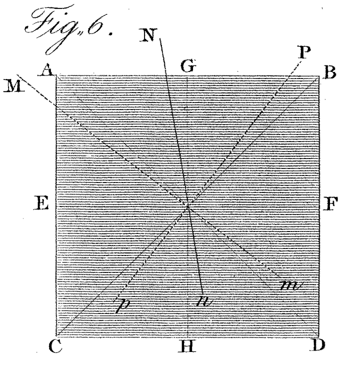


Fig. 7.

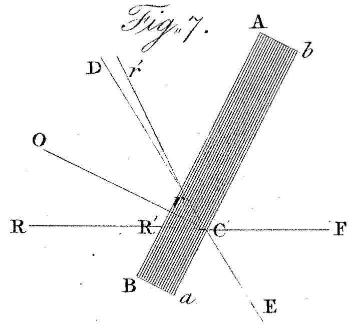


Fig. 8.

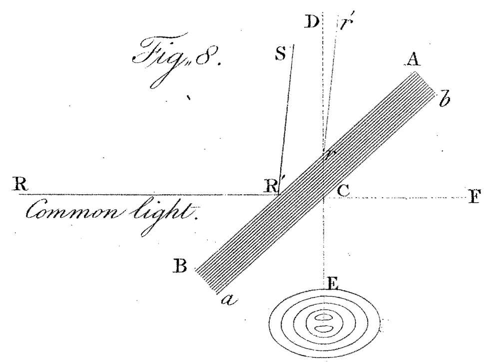


Fig. 9.

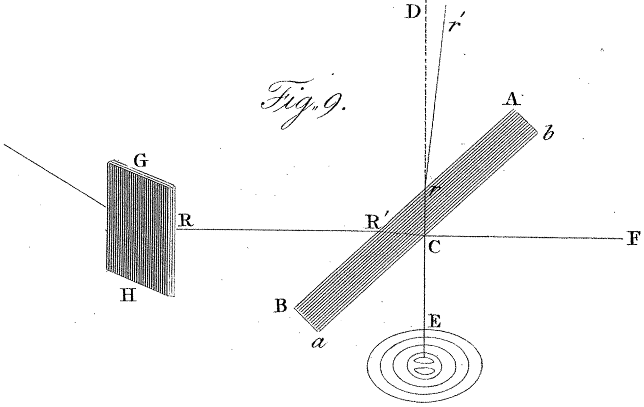


Fig. 10.

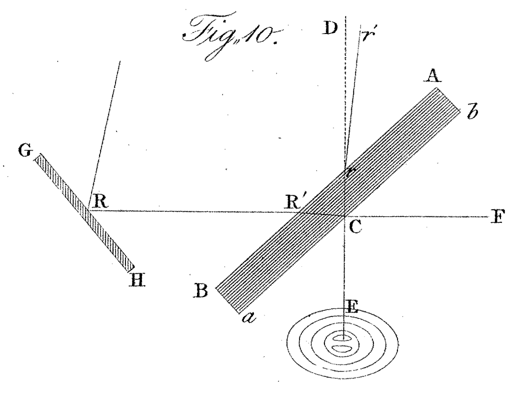


Fig. 1.

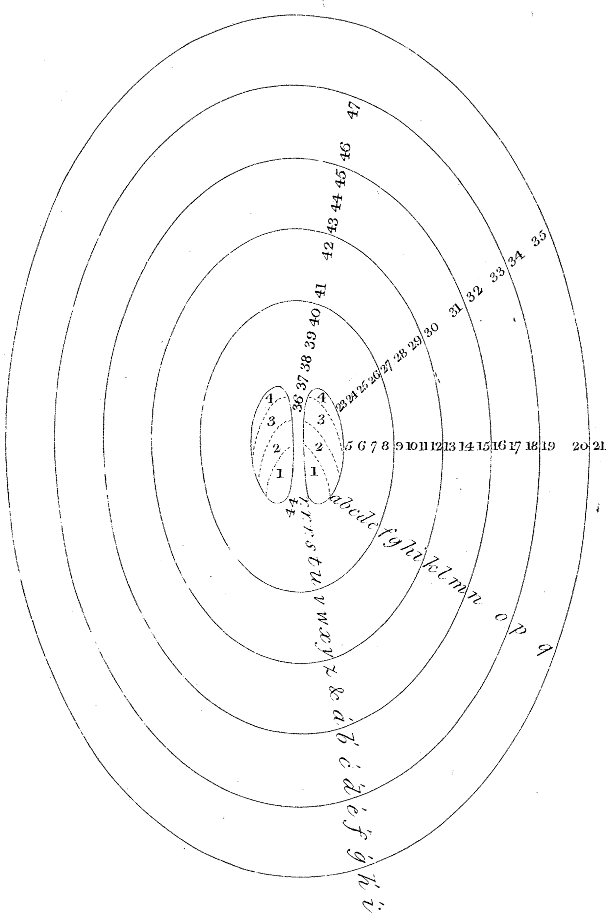
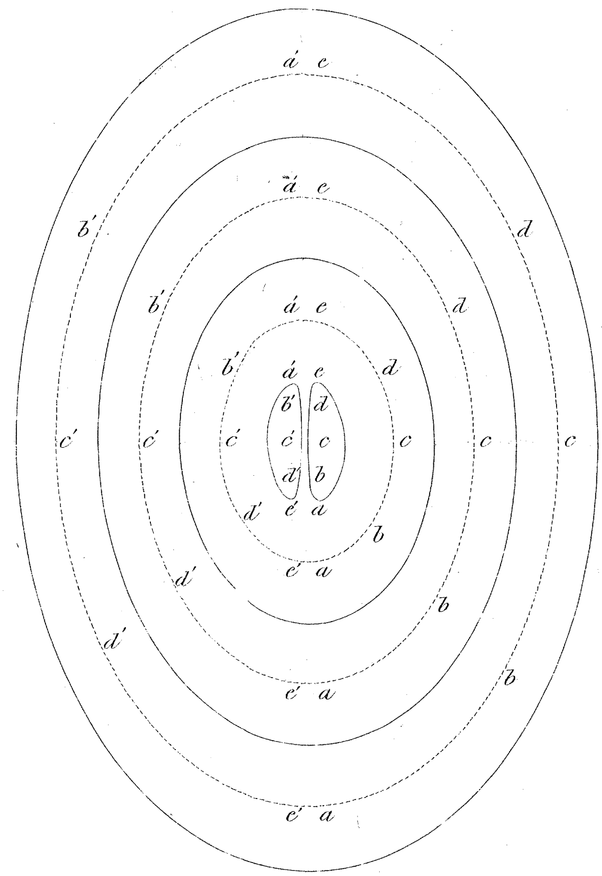


Fig. 2.



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